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GRAIN ENERGY OPPORTUNITIES IN SASKATCHEWAN

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Grain Energy Opportunities in Saskatchewan
Project # 20060051

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The objective in this project was to test various feed quality grains and other biomass pellets for potential Bio-renewable solid fuel. Locally produced samples of barley, canola, flax, oats, peas, rye, triticale, wheat, corn and spoiled canola were provided by Prairie Fire Grain Energy; along with a sample of wood pellets that were produced in British Columbia. The scope of this project did not allow for the testing of further bio mass pellet samples, although options were discussed and considered for future analysis.

The scope of this project was to study prairie grain samples and biomaterials as solid fuels to achieve the following objectives:

a) To determine the physical properties affecting handling and burning- the physical properties of the grain samples were determined through moisture content tests, density and porosity tests, friction and cohesion tests
b) To measure heat of combustion, chemical oxygen demand, and volume of ash; and
c) To measure emission gases resulting from burning in a typical grain burning stove.

Physical properties:

Moisture content ranged from the highest 15.62 % in the sample of rye to the lowest being wood pellets with a moisture content of 5.87% and the most commonly used fuel grains – wheat at 13.39% and corn at 15%. *(Table 1.)*

Density and porosity tests revealed that peas and canola had the lowest porosity (38-39%) due to their shape and oats had the highest porosity (approximately 61%). It was determined that low porosity could potentially affect combustion since less air space exists among/inside grains. The most commonly used grain fuels recorded porosity as follows: wheat (43.11%), rye (48.40%) and corn (39.40%). *(Table 2.)*

Friction and cohesion was determined with each sample with wood pellets presenting the highest coefficient and angle of internal friction due to the low moisture content. (5.87%). Wood pellets and rye showed the highest cohesion while peas showed the lowest among samples. The cohesion and friction properties of grain fuels were not considered factors in small scale grain fueled appliances such as the Prairie Fire PFG 060 which was used in this study and no problems were observed in the stove during experiments.

The heat of combustion was evaluated with flax and canola recording the highest at (7304 and 6800 cal/g) due to oil content and one the most common fuel grains wheat which registered at (4385cal/g).

Flue Gas Analysis was studied with no measurable amounts of Carbon Monoxide detected (Table 6.), although some hydrogen sulfide along with varying levels of methane, nitrogen and carbon dioxide were present. " *In the absence of detectable CO production, it is reasonable to assume that most of the available carbon in the grains was burned to CO_2 producing heat in the process." (Page 23)*

An economic analysis (Table 8.) determined that comparatively, grain fuel remains to be a cost effective alternative to traditional forms of heating. Despite the increased current (2007) feed grain prices used in this study, cost savings while using fuel grain are very significant. Coal (cost 7.45/million btu) was identified as the only other traditional fuel source to be competitive with grain. Although not suitable for use in the Prairie Fire PFG 060, spoiled canola was considered as a grain fuel option in this study due to its frequent availability and will be considered for future possibilities. "It *is important to note how much money the consumer will save by using the grain stove." (Page 25)*

Through this study, it was determined that the use of grain fuel is likely to be a positive alternative for the consumer to achieve substantial savings in heating costs. It has also been determined that through minor modifications in the PFG060, greater efficiencies can be achieved. (Page 27)

A) Abstract/ Summary

Prairie Fire Grain Energy Inc. employed the services of the University of Saskatchewan Agriculture & Bioresource Engineering Department to provide research personnel to analyze locally produced grain and commonly used biomass pellets in their PFG060 grain burning stove. The study identified physical properties of the grain/pellet samples, the combustion energy, and emissions produced from each sample and the cost effectiveness of using grain as an alternative to traditional sources of energy.

Samples used in this study include; feed grade wheat, rye, corn, canola, sample grade canola, flax, triticale, peas, oats and barley along with a sample of wood pellets which can be purchased locally. Through the analysis of these samples, it has been determined that grain fuel can offer consumers a positive alternative to traditional sources of energy providing both financial and environmental benefits.

B) Introduction – Pages 1 to 6

C) Methods – Pages 7 to 17

D) Results – Pages 17 to 25

E) Conclusion and recommendations – Page 26

F) Acknowledgements – Cover Page

G) Literature Cited – Pages 27,28

H) Appendices

I) Other

a. Personnel involved

i. Professor Oon-Doo Baik, Dr. Satya Panigrahi, Dr.Kamal Barghout, Mr. Bill Crerar, Dr. Shahram Emami, Delmer Hering, Janet Hering, Kimberly Kun, B.Comm

ii. Meetings with the research group took place on a regular basis through telephone conversation and organized meetings.

iii. Equipment used in the study was arranged and organized by the research team. The PFG 060 stove was supplied by Prairie Fire Grain Energy Inc. along with supplies and samples necessary to perform experiments.

iv. Photos – included

v. Expense Statement - Attached

Introduction

Modern society is highly energy intensive for production, processing, transportation and heating. Energy requirements continue to expand and increase, and western Canadian winters remain cold, global warming notwithstanding. The impending energy consumption gap has led researchers to pursue new energy sources and technologies, and to re-examine biorenewable solid fuels. A majority of conventional heating energy is obtained from fossil fuels, coal and petroleum (fuel oil and natural gas). These sources of energy are not renewable and their price is growing.

Agricultural products and biomass are one promising renewable sources of energy. Using grain as a source of energy in Prairies would reduce transportation, handling, processing, and storage costs. Additionally, surplus and off-grade agricultural materials can be used as a source of energy and will have a new market.

Many home and building owners use fossil heating fuels, such as oil or propane, for space heating. These fuels are often expensive and unstable in pricing, and are threatening the global climate and sustainability of communities. Proven alternatives to fossil heating fuels exist and are already in use across North America: Biomass fuels are a local, renewable resource for providing reliable heat. Grain energy sources are great alternatives to fossil heating fuels and present good biomass. Biomass is any biological material that can be used as fuel such as agricultural residues.

The use of grains as energy source is attractive to consumers because the grains are dry and so they are easily handled and because they have high heat energy per unit weight. Also, off market grains and lower quality are especially attractive to consumers for their relatively low prices.

The storage, moving and handling of energy grains is relatively easy. Farmers harvest, dry, convey, and store millions of bushels of these grains every year. The equipment to do all these things is ready available. Consequently, putting a grain storage system

together for a home heating set up is possible with augers, conveyors and storage bins which are readily available.

Advantages to Heating with Biomass

Using biomass fuels helps mitigate such environmental issues as acid rain and global climate change compared with burning high sulphur non-renewable coal. Perhaps the greatest advantage of biomass fuels, however, is that they cost on average 25-50 percent less than fossil heating fuels and are more stable in pricing.

It is unlikely that any future carbon or energy taxes will increase the cost of biomass fuels and are more likely to raise the cost of heating with fossil fuels. The technology is becoming well established in the North American market and the choice to heat with biomass fuels can be as simple as choosing a traditional fossil fuel heating system.

In addition, biomass from grain source:

- is convenient and easy to use, and can easily be bulk stored
- has a high energy content, and the technology is highly efficient
- is a clean-burning renewable fuel source
- can be produced from off market product
- is price stable compared to fossil fuels

Principle of Combustion

Combustion refers to the rapid oxidation of fuel accompanied by the production of heat. Complete combustion of a fuel is possible only in the presence of an adequate supply of oxygen. Oxygen is one of the most common elements on earth making up 20.9% of our air. Rapid fuel oxidation results in large amounts of heat. Solid or liquid fuels must be changed to a gas before they will burn. Usually heat is required to change liquids or solids into gases. Fuel gases will burn in their normal state if enough air is present.

Typically, 20-21% of air is oxygen. Most of the remaining is nitrogen, with traces of other elements. Nitrogen is considered to be a temperature reducing dilutant that must be present to obtain the oxygen required for in-air combustion.

Nitrogen reduces combustion efficiency by absorbing heat from the combustion of fuels and diluting the flue gases. This reduces the heat available for transfer through the heat exchange surfaces. It also increases the volume of combustion by-products, which then have to travel through the heat exchanger and up the stack faster to allow the introduction of additional fuel air mixture.

This nitrogen also can combine with oxygen (particularly at high flame temperatures) to produce oxides of nitrogen (NO_2, NO_2), which are toxic pollutants.

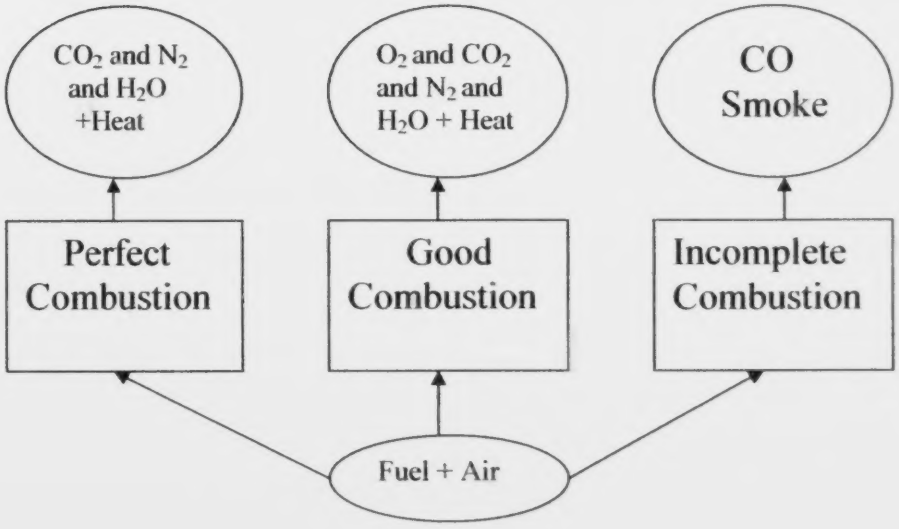
Carbon, hydrogen and sulphur in the fuel combine with oxygen in the air to form carbon dioxide, water vapour and sulphur dioxide releasing heat. Under certain conditions, carbon may also combine with Oxygen to form (toxic) carbon monoxide, which results in the release of a smaller quantity of heat but carbon burned to CO_2 will produce more heat per pound of fuel than when CO or smoke are produced.

Each kilogram of CO formed means a loss of 5654 kCal of heat. The objective of good combustion is to release all of the heat in the fuel. This is accomplished by controlling the elements of combustion which are (1) Temperature high enough to ignite and maintain ignition of the fuel, (2) Turbulence or intimate mixing of the fuel and oxygen, and (3) Time sufficient for complete combustion.

Commonly used fuels like natural gas and propane generally consist of carbon and hydrogen. Water vapour is a by-product of burning hydrogen. This robs heat from the flue gases, which would otherwise be available for more heat transfer. For example, natural gas contains more hydrogen and less carbon per kg than fuel oils and as such produces more water vapour. Consequently, more heat will be carried away by exhaust while firing natural gas.

Too much, or too little fuel with the available combustion air may potentially result in unburned fuel and carbon monoxide generation. A very specific amount of O_2 is needed for perfect combustion and some additional (excess) air is required for ensuring complete combustion. However, too much excess air will result in heat and efficiency losses.

The following flowchart shows 3 different combustion processes:



The following chemical formulas show the combustion process with the released amount of heat.

$C + O_2 \rightarrow CO_2 + 8084$ kCals/kg of Carbon

$2C + O_2 \rightarrow 2\,CO + 2430$ kCals/kg of Carbon

$2H_2 + O_2 \rightarrow 2H_2O + 28{,}922$ kCals/kg of Hydrogen

$S + O_2 \rightarrow SO_2 + 2{,}224$ kCals/kg of Sulphur

Not all of the heat in the fuel is converted to heat to be exchanged with room heat. Usually all of the hydrogen in the fuel is burned and most boiler fuels, allowable with today's air pollution standards, contain little or no sulphur. So the main challenge in combustion efficiency is directed toward unburned carbon (in the ash or incompletely burned gas), which forms CO instead of CO_2.

Control of Air and Analysis of Flue Gas

In practice, mixing of air and fuel is never perfect, a certain amount of excess air is needed to complete combustion and ensure that release of the entire heat contained in fuel. If too much air than what is required for completing combustion were allowed to enter, additional heat would be lost in heating the surplus air to the chimney temperature. This would result in increased stack losses. Less air would lead to the incomplete combustion and smoke. Hence, there is theoretically an optimum excess air level for each type of fuel.

Thus in actual practice, the amount of combustion air required will be much higher than optimally needed. Therefore some of the air gets heated in the furnace or boiler and leaves through the stack without participating in the combustion

As it is important to optimize excess of air needed for the combustion process we need to quantify flue gases for that purpose as well. To do this optimally, all the flue gases as well as the elements in each grain fuel before combustion (C, N, O_2, S….) that contribute to the process of combustion should be quantified which is beyond the scope of the current study.

Chemical analysis of the gases is an objective method that helps in achieving finer air control. By measuring carbon dioxide (CO_2) or oxygen (O_2) in flue gases by continuous recording, the excess air level as well as stack losses can be estimated. This method also was not followed due to time and equipment limitations. To achieve finer air control for the purpose of optimizing combustion process, we calculated oxygen demand for the process and accordingly estimated the criterion for the intake air controlling process.

In the present study, samples of flue gases were sampled and analyzed by gas chromatography.

Emission Gases

Green house gases were the main concern for analysis as it is important to quantify and compare the released gases from the combustion of various grain fuels. The analysed gases in this study were: Methane, CO, CO_2, and N_2O. Methane is a relatively potent greenhouse gas with a high global warming potential (i.e., warming effect compared to carbon dioxide). The third assessment report of the Intergovernmental Panel on Climate Change (IPCC) stated that when averaged over 100 years each kg of CH_4 warms the Earth 25 times as much as the same mass of CO_2. Nitrogen (N_2) was quantified as a reference, while oxygen was measured to track oxygen demand.

The Scope of the Study

The scope of this study was to study some prairie grains and biomaterials as solid fuels. The specific objectives were a) to determine the physical properties affecting handling and burning; b) to measure heat of combustion, chemical oxygen demand, and volume of ash; and c) to measure emission gases resulting from burning in a typical grain-burning stove

Materials

Grain samples (barley, canola, flax, oats, peas rye, triticale, red spring wheat, wood pellet, corn and spoiled canola were sourced clean bin-run from the local farmers and Prairie Fire Grain Energy Inc in the Saskatoon-Humboldt area of Saskatchewan. Samples were stored in sealed plastic bags to maintain the initial moisture content as increasing moisture content can negatively impact heat of combustion (Riggins et al. 1980). Moisture was measured but not adjusted, so as to represent typical bin-run grain as would be used for burning in stoves.

Experimental Methods

Physical Properties of Grain Fuel

Moisture content of the intact (non-ground) samples was determined by the oven method at temperature and duration listed in ASAE standard S352.2 (ASAE 1998).

To determine particle density, a gas pycnometer (Multi Pycnometer Model MVP-2, Quantachrome Corp., Boynton Beach, FL) (Figure 1) was employed to measure the solid volume of particles in a sample. The corresponding mass of the sample was also measured. The particle density was calculated using the following equation:

$$\rho_t = \frac{m}{V_s} \tag{1}$$

where ρ_t = particle density (kg/m^3); m = mass of sample in the cylinder (kg); and V_s = volume of solid (m^3).

Figure 1. Gas pycnometer for measuring the solid volume of sample

To measure the volume of solid in the gas pycnometer, the gas was pressurized in the reference volume to about 17 psi (P_1) and then the gas was allowed into the sample cell to reach a constant pressure (P_2). The following equation was used to determine volume of solid:

$$V_s = V_{cell} - V_R\left[\frac{P_1}{P_2} - 1\right] \tag{2}$$

where V_s = volume of solid (cm^3); *Vcell* = volume of the cell (cm^3); *VR* = reference volume for the large cell (cm^3); P_1 = pressure reading after pressurizing the reference volume (psi); and P_2 = pressure reading after including volume of the cell (psi).

Bulk density was measured using a standard 0.5-L cylindrical density cup filled using a density funnel, with its discharge opening located 55 mm above the top edge of the container. The funnel was removed from top of the container and the sample on the container was leveled by rolling a round stainless steel bar across the container in two perpendicular directions. Then, the container was weighed. The bulk density was calculated using the following equation:

$$\rho_b = \frac{m}{V_c} \tag{3}$$

where ρ_b = bulk density (kg/m^3); m = mass of sample in the cylinder (kg); and V_c = volume of cylinder (m^3).

Porosity was determined from bulk density and particle density using the following equation (Mohsenin 1986; Fang et al. 2000):

$$\varepsilon = \left(1 - \frac{\rho_b}{\rho_t}\right) \times 100 \tag{4}$$

where: ε = porosity (%); ρ_b = bulk density (kg/m^3); and ρ_t = particle density (kg/m^3).

Since porosity was calculated using bulk density and particle density values resulting from measurement, the calculated error is the root of the individual errors (Equation 5). This kind of error calculation was discussed by Ma and co-workers (1998) for determination of error of secondary quantities.

$$\Delta\varepsilon = 100 \times \sqrt{\left(\frac{\partial\varepsilon}{\partial\rho_b}\Delta\rho_b\right)^2 + \left(\frac{\partial\varepsilon}{\partial\rho_t}\Delta\rho_t\right)^2} \tag{5}$$

where: $\Delta\varepsilon$ = error of porosity;

$\Delta\rho_b$ = error of bulk density; and

$\Delta\rho_t$ = error of particle density.

In the current study, each value in Equation 5 is given by:

$$\frac{\partial \varepsilon}{\partial \rho_b}\Delta\rho_b = -\frac{1}{\rho_t}\Delta\rho_b \tag{6}$$

$$\frac{\partial \varepsilon}{\partial \rho_t}\Delta\rho_t = \frac{\rho_b}{\rho_t^2}\Delta\rho_t \tag{7}$$

Therefore, the error of porosity is obtained by substituting Equations 6 and 7 into Equation 5:

$$\Delta\varepsilon = \sqrt{\left(-\frac{1}{\rho_t}\Delta\rho_b\right)^2 + \left(\frac{\rho_b}{\rho_t^2}\Delta\rho_b\right)^2} \tag{8}$$

To determine internal friction and cohesion, a Wykeham Farrance shear box apparatus (Wykeham Farrance International Ltd., Slough, UK) equipped with a shear box measuring 100 mm square and motor assembly was used. Both lower and top boxes of the apparatus were filled with sample using a funnel positioned 55 mm above the top edge of the box. The lower box moved at a constant speed of 0.6 mm/min. Shear stress at four different normal loads (100, 200, 300, and 400 N) were measured with the setup shown in Figure 2. The test was conducted in three replicates, as explained by Peleg (1977), Duffy and Puri (1996), and Tabil and Sokhansanj (1997). Mohr-Coulomb equation (Equation 9) shows the relationship between shear stress and normal stress as used by Peleg and co-workers (1973), Chancellor (1994), Duffy and Puri (1996), and Puchalski and Brusewitz (1996). Regression analysis was conducted to calculate the angle/coefficient of internal friction and cohesion.

$$\tau = C_c + \tan\phi_i \ \sigma \tag{9}$$

where: τ = shear stress (Pa); C_c = cohesion (Pa); ϕ_i = angle of internal friction; and σ = normal stress (Pa).

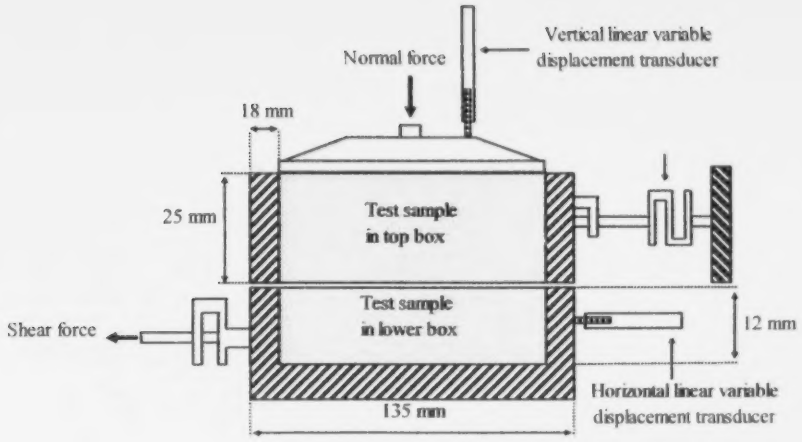


Figure 2. Schematic of Wykeham Farrance shear box apparatus.

Heat of Combustion, Chemical Oxygen Demand, and Volume of Ash

Heat of Combustion

Gross heat of combustion of samples was determined using an oxygen bomb calorimeter (Series 1300 Plain Calorimeter, Parr Instrument Company, Inc., Moline, IL). The gross energy has the latent heat of vaporization recovered during the condensation of the water vapour in the bomb calorimeter, unlike net energy (Riggins et al. 1980). The colorimeter was standardized using 1.00 g Parr standard benzoic acid, formed to a pellet, with calorific value of 6319 cal/g. A single length of fuse wire having 10 cm long and 2.3 cal/cm heat of combustion was used to combust the sample in the bomb calorimeter. About 1.00 g sample was measured in metal combustion capsule and placed in the sample holder in the bomb head (Figure 3). The fuse wire was connected to the electrodes of bomb head. The bomb head was fitted to the bomb cylinder. The bomb was sealed by turning the screw cap down firmly. The bomb was filled with oxygen at 25 psi gage pressure and emptied three times using a valve on the bomb to purge air inside of the bomb (Figure 4). Then, the bomb with 25 psi oxygen was submerged in an oval bucket containing 2000 g deionized water. The external connections of electrodes were

connected and the colorimeter was covered by its lid (Figure 5). The stirrer was started for 5 min to attain thermal equilibrium between bomb and water in the bucket. A thermocouple was passed through the hole in the lid to measure the water temperature (Figure 6). The thermocouple was connected to a Campbell data logger (Model CR10X, Campbell Scientific, Inc. Logan, UT) to record temperature to the nearest 0.001°C in 1.0 s intervals. The data logger was turned on followed by pressing button on ignition unit to combust sample in bomb. Data was recorded for about 5 min to measure temperature rise and then data was transferred from data logger to a laptop computer. The bomb was lifted from the bucket and the remaining oxygen was released. The bomb was opened and the length of unburned fuse wire was measured and subtracted from 10 cm initial length. The following equations were used to calculate the heat of combustion (Parr Instrument Company 1970):

$$W = \frac{Hm_a + e}{t} \tag{10}$$

$$H_g = \frac{tW - e}{m} \tag{11}$$

Where W = energy equivalent of calorimeter (cal/°C); H = gross heat of combustion of standard benzoic acid (cal/g); m_a = mass of benzoic acid; t = corrected temperature rise (°C); e = correction for heat of firing fuse wire (cal); m = mass of sample in combustion capsule; and H_g = heat of combustion of sample.

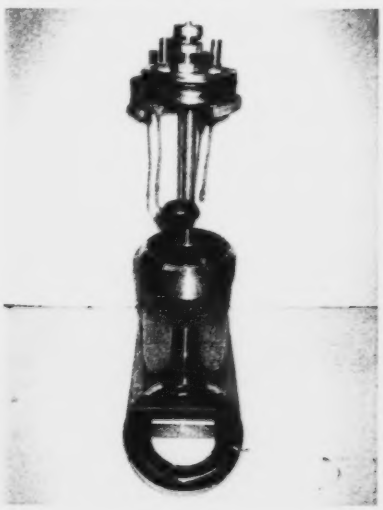


Figure 3. Bomb calorimeter and related parts.

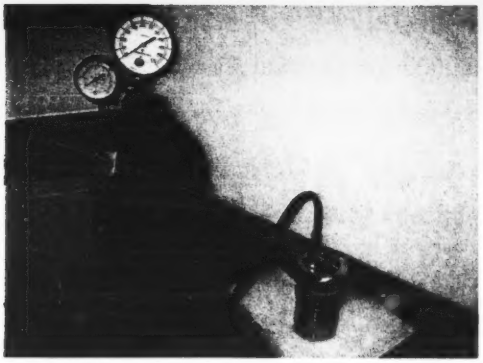


Figure 4. Filling bomb calorimeter with oxygen.

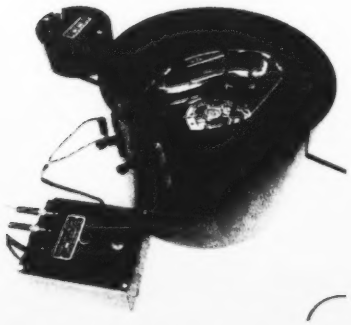


Figure 5. Bomb calorimeter and bucket.

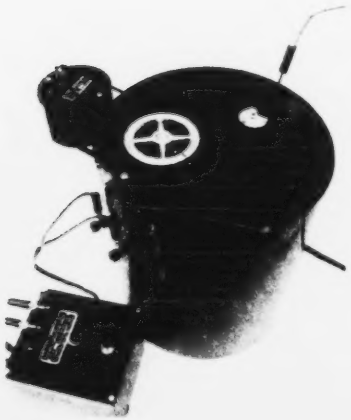


Figure 6. Bomb calorimeter, stirrer and thermocouple.

Ash Content and Ash Density

To measure the ash content, the samples were tested according to AACC Method 08-03 standard; Ash - Rapid (2 hour, 600°C) Method. To measure the ash bulk density ash was weight and volume of ash was measured by placing the ash in a measuring tube and the bulk density was determined accordingly.

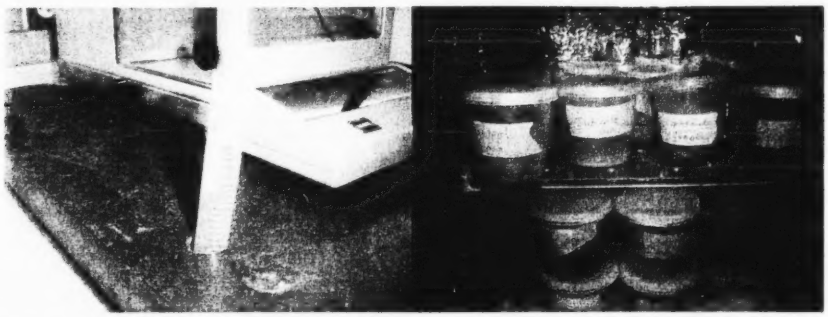


Figure 7. Ash density testing tube and digital scale (left), Ash content containers (right)

Chemical Oxygen Demand

We mean by Oxygen demand the percent oxygen needed for complete combustion. This is important to design ducting and control intake (combustion) air. Insufficient air will lead to incomplete combustion and production of hazardous carbon monoxide. Supplying excess combustion air will lead to hot air loss up the chimney. So, it is desirable

To estimate the intake-air needed for complete combustion of grain, we have actually quantified oxygen gas needed to burn each grain completely (optimized by visual inspection by setting the burn rate at indicator "5" of full range) and computed the amount of intake-air accordingly. We thus have computed the amount of air needed for combustion at grain feed rate of "5" as litre/hr and adjusted the volume of intake-air at the specified temperature and related that to the grain feed rate. The grain feed rate was estimated manually.

We measured the oxygen demand by subtracting percent oxygen intake of ambient air (measured to be 21.58% at the time of the experiment) from percent oxygen out in exhaust gas for each grain fuel. We measured the intake air velocity and calculated the intake air flow rate to be 32.75 CFM. We calculated the flow rate of intake air needed for each grain fuel and added 10% to ensure complete combustion under variable conditions. We also calculated the excess of air flow to be adjusted. From table 7 ideally the combustion fan should be adjusted to maximum efficiency for each type of grain fuel by reducing excess air flow to the needed flow level (column 2). In practice, the needed airflow+10% values for the wood pellets and most of the grains ranged from 11-13%, with peas coming in at 9% and oats just over 15%. So, unless a stove was being set up for single fuel use with oats or peas, adjustment of airflow would not really be practical.

Grain Stove Testing and Emission Sampling

Set up for Stove Operation

An insulated room outside the Hardly Laboratory in the department of Agricultural & Bioresource Engineering, University of Saskatchewan was specially built to house the stove. The stove was set up with 3" air intake and flue gas exhaust tubes and proper clearance was ensured between the air intake and the chimney to ensure non-contamination of intake air with flue gases. Ambient temperature at the time of experiments was recorded to calculate the density of intake volume air. Samples of intake air were also taken for gas chromatographic analysis to quantify composition to establish baseline composition and ensure non-contamination of combustion air with flue gases. The following is a picture of the insulated room:

Figure 8. The insulated room (left), Dr. Oon-Doo Baik with the Grain stove (Right)

Flue Gas Sampling

To take samples of flue gases for analysis we operated the stove at a steady state and at a feed rate of "5" on the auger speed, which is half of maximum. Samples were taken only after we ensured a steady state of burning. Intake-air flow rate was taken by measuring the flow rate from the intake tube, using a TSI Hot-wire anemometer. Average rate of burning of grain fuel was measured manually by timing the combustion of 1 litre of grain fed in the feed hopper for 3 different grains at grain feed rate setting of "5" and converted to kg/hr utilizing the bulk density of each grain. Quantifying oxygen demand for each grain was done by measuring oxygen content in the intake-air and the flue gas.

Flue Gas Analysis

Gas analysis was done at the University of Saskatchewan Soil Science laboratory (Dr. Richard Farrell) by employing gas chromatographic analysis with the following criteria;

The instrument used for N_2O and methane detection is a Varian CP-3800 gas chromatograph. Nitrous oxide is detected with one of 2 ECD's (electron capture detectors). The columns used are Poraplot Q coated plot fused silica 10 meters in length x .32 mm in diameter, with a .32 um film thickness. Although these 2 columns are the same, they use different parameters to compensate for manufacturing differences.

The detector used for methane detection is a FID (flame ionization detector). The column used is a plot fused silica 25 meters in length, .53 mm in diameter, coated with carboplot P7, with a film thickness of .25 um. The carrier gas for all detectors is helium, and the make-up for the ECD's is argon with 5% methane, also called P5.

The instrument used for CO_2 analysis is a Varian Micro-GC CP-2003. The CO_2 is identified using a TCD (thermal conductivity detector) The column used is a Poraplot U 10 meters in length and .32 mm inner diameter.
Oxygen is identified using a TCD and a molecular sieve column 10 m in length.

Cost Effectiveness

The economic analysis of the energy grains used to operate the heating system in hand is based on price of the grain versus its combustion energy yield. It is preliminary analysis based on whether the grain energy fuels are likely to be a cost-effective alternative to heating with fossil fuels.

The prices of the market grains presented in this study are the prices that must be paid to the producer presented by Grain Energy Inc. It should be noted that the presented energy yield is based on the energy values obtained by the heat combustion energy testing using the bomb calorimeter conducted in the course of the project with 90% efficiency of the stove.

The analysis compares the price (on an energy content basis) for all of the energy grains tested and evaluated against traditional heating fuels energy yield and current prices. The grains are used to power the heating unit: Prairie Fire Model # PFG 060.

The tested energy grains found to compete with traditional fuels. Table1 presents energy grain cost (per million Btu).

To be able to compare heating with energy grains with other heating fuels we looked at a number of factors. Not only is price of the fuel important, but also the heating efficiency of the heating system and the energy content of a unit of each fuel. The following is the formula which we used to calculate the cost per Million Btu's of useable energy. This formula takes into account the following factors:

1. Cost per unit/per lb of fuel.

2. Energy content per pound
3. heating efficiency

Formula:

Cost per Million Btu's of useable energy = (Cost Per Pound of Fuel ×1,000,000) ÷ (Energy Content Per Pound of Fuel (Btu) × Heating Efficiency)

Example: Lets look at an example where we used Canola at $207/MT with our stove which has heating efficiency of 90%. What is the cost per million Btu's of useable energy?

Canola cost = $207/MT

Cost/lb = (Cost/MT × kg-conversion factor × lb-conversion factor) = 207 × 1000 × 0.45359 = $0.94

Energy content per pound (Btu/lb) = Energy content per gram × conversion factor (1.8)

Heating efficiency = 90% = 0.9

Dollars per Million Btu's Usable Energy = (Cost per lb of fuel ($ 0.094) × 1000,000) ÷ (Energy content per pound ($12176 Btu/lb) × Heating Efficiency (0.9)) = $8.57

Results and Discussion

Moisture Content

Table 1 presents moisture content of the as-received samples. Wood pellets had the lowest moisture content (approx 6%); while the rye and pea samples, at nearly 16% had the highest moisture content. The various grains compositions of starch, protein, and oil have varying natural 'safe' maximum moisture contents for long term storage without degradation or spoilage; these maximum 'dry' values are given in Table 1. Note that the canola and oats samples are slightly 'tough'; this would not be unusual for off-grade grain used for fuel. Drying grain to lower moisture contents could require artificial heat/energy inputs and increased production costs, which might not be feasible for slightly tough grain destined for fuel use. The low moisture content of pellet wood was

probably related to heat generation during pelletizing resulting in moisture loss from sample.

Table 1. Moisture content of fuel grain samples (n = 2).

Sample	Moisture content (% w.b.)	Canadian Grain Commission Specs (2007)	
		Dry under	Tough
Barley	13.51 ± 0.00	14.8	14.9-17.0
Canola	11.25 ± 0.07	10.0	10.1-12.5
Flax	7.37 ± 0.04	10.0	10.1-13.5
Oats	14.91 ± 0.04	13.5	13.6-17.0
Peas	15.60 ± 0.01	16.0	16.1-18.0
Rye	15.62 ± 0.05	14.0	14.1-17.0
Triticale	13.29 ± 0.02	14.0	14.1-17.0
Wheat	13.39 ± 0.05	14.5	14.6-17.0
Wood pellet	5.87 ± 0.02	-	-
Corn	15 ± 2	15.5	15.6-17.5
Spoiled Canola	9.1 ± 0.7	10.0	10.1-12.5

Density and Porosity

Table 2 shows particle density, bulk density, and porosity of samples. Peas and Canola had the lowest porosity (38-39%) due to their geometric shape and roundness while oats had the highest porosity (approximately 61%). Low porosity potentially affects combustion since less air space exists among/inside grains.

Table 2. Particle density, bulk density, and porosity of fuel grain samples (n = 3).

Sample	Particle density (kg/m^3)	Bulk density (kg/m^3)	Porosity (%)
Barley	1376.8 ± 0.7	654 ± 1	52.5 ± 0.1
Canola	1112.5 ± 0.8	678 ± 1	39.1 ± 0.1
Flax	1143.1 ± 0.5	670.8 ± 0.6	41.32 ± 0.06

Oats	1333.0 ± 0.3	522 ± 2	60.9± 0.2
Peas	1351.3 ± 0.9	834.8 ± 0.9	38.22 ± 0.08
Rye	1338.5 ± 0.6	690.7 ± 0.6	48.40 ± 0.05
Triticale	1416 ± 1	736.8 ± 0.6	47.97 ± 0.06
Wheat	1420.9 ± 0.6	808.3 ± 0.3	43.11 ± 0.03
Wood pellet	1436.83 ± 0.79	693 ± 4	51.8 ± 0.3
Corn	1298 ± 2	786.3 ± 0.2	39.40 ± 0.06
Spoiled Canola	1050 ± 2	522 ± 4	50.3 ± 0.5

Friction and Cohesion

Coefficient and angle of internal friction and cohesion of samples are presented in Table 3. All samples fitted to Mohr-Coulomb equation very well with high coefficient of determination (R^2) and low standard error of estimate (SSE). Wood pellet presented the highest coefficient and angle of internal friction which was due to the low moisture content (5.87% w.b.). As the moisture content decreases the coefficient and angle of internal friction increase. As expected, flax had the lowest coefficient and angle of internal friction due to its smooth surface and waxy surface. Oats, after flax, had low coefficient and angle of internal friction. Wood pellet and rye showed the highest cohesion. Peas showed the lowest cohesion among samples. The cohesion and friction properties of grain fuels are potentially important in designing larger handling and storage systems for solid-fuel burning facilities; no handling problems were observed in the grain stove during the experiments described here.

Table 3. Coefficient and angle of internal friction and cohesion of fuel grain samples (n = 3).

Sample	μ_i	ϕ_i	Cohesion		
		(Degree)	Estimate (kPa)	R^2	SEE
Barley	0.49	25.91	1.93	1.00	0.42
Canola	0.55	28.69	1.15	0.98	0.88

Flax	0.24	13.43	1.65	0.98	0.41
Oats	0.36	19.67	2.55	0.99	0.47
Peas	0.65	32.89	1.04	0.99	0.76
Rye	0.46	24.67	3.12	0.99	0.53
Triticale	0.49	25.94	1.89	0.99	0.68
Wheat	0.47	25.07	2.51	1.00	0.40
Wood pellet	0.85	40.38	3.92	0.94	2.70
Corn	0.85	25.07	3.92	0.94	2.70
Spoiled Canola	0.85	40.38	3.92	0.94	2.70

μ_i: coefficient of internal friction

ϕ_i : angle of internal friction

SEE: standard error of estimate

Heat of Combustion

Table 4 shows the heat of combustion of test samples. Flax and Canola had the highest heat of combustion (6800 and 7300 cal/g) due to high oil content. The cereal grain and peas heats of combustion were in the range of 4000 (rye) to 4400 cal/g (oats, peas)

Table 4. Heat of combustion of fuel grain samples (n = 3).

Sample	Heat of combustion (cal/g)
Barley	4169 ± 151
Canola	6765 ± 70
Flax	7304 ± 328
Oats	4380 ± 78
Peas	4440 ± 398
Rye	4025 ± 62
Triticale	4362 ± 21
Wheat	4385 ± 67
Wood pellet	4934 ± 79
Corn	4272 ± 117
Spoiled Canola	6170 ± 74

Ash Content and Ash Density

Table 5 shows ash volume and ash bulk density. Wood pellets had the lowest ash content (0.3%) while rye and oats and triticale had 1-2% ash content. Corn, peas, wheat, flax and canola had ash contents increasing form 2.3 to just over 4%, respectively while spoiled canola had an ash content of slightly over 5%. Oats had a low ash density (80 kg/m^3) comparable to wood pellet ash and rye (107 and 104 kg/m^3). Spoiled canola, corn, triticale, barley, wheat, canola and flax had ash densities ranging from 120 to 209 kg/m^3, while peas had the highest measured ash density at 304 kg/m^3. Obviously a minimal amount of ash production is most desirable. Meanwhile a denser ash will be more compact, causing less buildup and fouling in the firebox, and be less prone to blowing around/being carried into the stack exhaust as fly ash.

Table 5. Ash content and ash bulk density

Ash Sample	Ash content Wt % of Ash	Ash bulk density (kg/m^3)
Barley	3.32 ± 0.01	170 ± 10
Canola	4.05± 0.05	200 ± 10
Flax	3.21 ± 0.08	209 ± 3
Oats	1.55 ± 0.04	80 ± 2
Peas	2.61 ± 0.04	304 ± 8
Rye	1.0 ± 0.1	103.7 ± N/A
Triticale	1.89 ± 0.05	170 ± 10
Wheat	2.95 ± 0.04	190 ± 10
Wood pellet	0.29 ± 0.06	107 ± N/A
Corn	2.34 ± 0.03	156 ± 9
Spoiled Canola	5.09 ± 0.04	120 ± 10

Flue Gas Analysis

Table 6 Results of flue gas analysis from grain fuels burned in the grain stove (n=3).

grain	N_2O (%)	Methane (ppm)	Nitrogen (%)	CO_2 (ppm)	CO (%)
peas	7.63 ± 3.9	1.41 ± 0.24	78.75 ± 0.08	42905 ± 9323	-
corn	4.10 ± 1.4	1.09 ± 0.06	78.95 ± 0.07	54796 ± 8494	-
rye	8.12 ± 3.3	1.20 ± 0.20	78.80 ± 0.2	48451 ± 13659	-
triticale	8.69 ± 1.2	0.97 ± .14	78.6± 0.1	40597 ± 4775	-
oats	8.06 ± 0.43	2.22 ± 1.3	78.60 ± 0.1	30429 ± 7191	-
canola	11.14 ± 0.98	142 ± N/A	79.4 ± 0.6	36988 ± 14362	-
wood pellets	0.66 ± 0.05	1.09 ± 0.04	78.81 ± 0.06	50086 ± 1858	-
flax	4.38 ± 3.7	674 ± N/A	79.7 ± 0.4	62070 ± 800	-
barley	9.08 ± 2.6	1.02 ± 0.03	78.94 ± 0.04	55569 ± 4170	-
Wheat	9.10 ± 60	1.35 ± 0.31	78.7 ± 0.2	55397 ±	-

				10466	
Ambient Air	0.51± 01	1.57± 0.05	78.66 ± 0.03	404 ± 12	-
Laboratory Air	N/A	N/A	77.5 ± N/A	412 ± N/A	-
Car exhaust	N/A	N/A	84.8 ± N/A	130660 ± N/A	2.35

Carbon Monoxide (CO) was not detected in measurable amounts for any of the flue gas samples. Some hydrogen sulfide (H_2S) was detected in the flue gases for the canola, flax grain due to their high oil content while barley showed a less significant amount of the gas. H_2S gas was not quantified due to lack of calibration standards in the present study. Nitrogen contents were pretty consistent throughout, ranging from 78.6 to 79.7%, similar to ambient air, and suggesting that 20-21% oxygen was present in the flue gases, with much smaller amounts of combustion e.g. CO_2 and greenhouse gases.

There was a wide variation of carbon dioxide concentration; oats, canola, triticale, peas and rye produced CO_2 concentrations ranged from 30,400 to 48,500 ppm compared to 50,000 ppm for wood pellets, while wheat, barley and flax produced CO2 concentrations ranging from 55,400 to 62,000 ppm. It is important to note that all experiments from which these values were taken were for a single feed rate setting and have not been adjusted for fuel mass consumption or heat value produced. In the absence of detectable CO production, it is reasonable to assume that most of the available carbon in the grains was burned to CO_2 producing heat in the process.

To compare with ambient air of concentrations of 404 ppm CO_2, 1.57 ppm Methane and 0.51 % N_2O, flax emitted much larger quantities of Methane gas than the rest of 674 ppm (way above the average) followed by Canola 142 ppm while for CO2 flax was the highest with 62070 ppm and for N_2O Canola was the highest with 11 %.

Oxygen Demand

We calculated the oxygen demand and the needed air flow for perfect combustion. Also Excess of air flow was calculated for each grain to help optimize efficiency.

Table 7 shows Oxygen demand for each grain fuel

Table 7. Oxygen demand of grain fuel @ "5" feed rate (n=3)

Grain fuel	Oxygen in Exhaust Gas %	Oxygen Demand (%)	Needed Airflow + 10% (CFM)	Excess of air flow (CFM)
Barley	15.19	6.40 ± 0.45	12.99	23.03
Canola	16.35	5.24 ± 0.02	11.22	24.80
Flax	13.73	7.85 ± 0.78	15.19	20.83
Oats	17.88	3.71 ± 1.1	8.91	27.11
Peas	16.51	5.08 ± 1.5	10.98	25.04
Rye	15.92	5.66 ± 0.51	11.87	24.15
Triticale	16.74	4.84 ± 0.98	10.63	25.40
Wheat	15.48	6.10 ± 0.21	12.54	23.49
Wood pellet	15.84	5.74 ± 0.91	11.99	24.03
Corn	15.22	6.37 ± 1.9	12.94	23.08

Economic Analysis:

Table 8. Energy Price vs. Energy Yield

1. Grain energy source					
Energy source	**$Fuel Cost/unit** [1]	**$Fuel Cost/lb**	**Energy Content (Btu/lb)**	**Estimated Appliance Efficiency %**	**$Energy Cost /Million Btu**
Barley	3.5/bu	0.0760	7505	90	11.27
Canola	207/MT	0.09393	12176	90	8.57
Flax	6.76/bu	0.1352	13146	90	11.43
Oats	80/MT	0.0363	7884	90	5.11
Peas	4.5/bu	0.0750	7993	90	10.43
Rye	3.4/bu	0.0654	7245	90	10.03
Triticale	3.4/bu	0.0654	7852	90	9.25
Wheat	4.75/bu	0.0848	7894	90	11.94
Wood Pellets	0.3/kg	0.1361	8882	90	17.02
Corn	190/MT	0.08621	7690	90	12.45
Spoiled canola	100/MT	0.0454	11105	90	4.54

2. Other energy sources				
Energy source	**$cost/unit**	**Energy Content**	**Appliance Efficiency %**[6]	**$Cost/Million Btu**
Propane[3]	0.477/litre	18952 Btu/litre	85	29.61
Electricity[4]	0.103/kwh	3414/Kwh	100	30.16
Natural Gas[2]	0.4436/m^3	35375 Btu/m^3	85	14.75
Coal[5]	0.0313/lb	7000 Btu/lb	60	7.45
Oil[7]	0.83/litre	36681 Btu/litre	85	26.62
Wood[8]	200/cord	16,464,000 Btu/cord	60	20.24

[1] The price is based on as unconditioned crop provided by Prairie Fire Grain Energy Inc-Bin run grain prices

[2] Price taken as an average of the Grain Energy Inc rental property gas bill from Aug 2006 to Aug 2007 for a 1000 sq ft house in Saskatoon

[3] 47.7 cents/litre today's price; provided by Prairie Fire Grain Energy Inc as of Aug 2007

[4] Average cost per month of $425; provided by Prairie Fire Grain Energy Inc as of Aug 2007

[5] $39 per MT and an average delivery cost of $30; provided by Prairie Fire Grain Energy Inc as of Aug 2007

[6] These are typical efficiencies. Actual efficiencies can vary. Unit costs of different energy sources may vary due to market conditions.

[7] Price taken as $0.83/litre; provided by Prairie Fire Grain Energy Inc as of Aug 2007

[8] Price taken as $200/cord; provided by Prairie Fire Grain Energy Inc as of Aug 2007

From the above table, spoiled canola is the cheapest to burn in the stove followed by Oat while comparing with other heating fuels; coal is most competitive with a price of $7.45/Million Btu.

It is important to note how much money the consumer will save by using the grain stove. An example: Electricity - Average cost per month of $425 (average of actual $ spent in two farming operations) which includes all power and taxes, surcharges, etc., with the usage at 49,500 KWh for one year period. This is about 169 Million Btu per year worth of electricity at a price of $5097.04. If the consumer needs to use the grain stove for heating and spoiled canola to power it, it will cost him only $767.26. That is a huge savings!! This doesn't include the unit price and installation (life cycle cost). The total

cost to purchase, own, and operate the stove over its entire life. The life cycle costs of the stove heating system can be compared to determine which option will be the least expensive to own and operate over the entire expected life of the stove-heating system.

Recommendation

It is important to quantify sulphur gas components in the grain fuel combustion exhaust gases due to its negative environmental effect. In particular, we need to quantify SO_2 and H2S gas. Unfortunately this was not covered in this study due to the limitation of the gc equipment used.

For the stove in hand, we recommend the unit should be optimized by controlling the air-intake fan for perfect combustion air need. This is an important step toward optimization of the efficiency of the stove as excess of air pumped to the combustion chamber assists in larger heat loss to the chimney. Therefore the combustion fan should be adjusted to maximum efficiency by reducing excess air flow to the needed flow level (column 2 in table 7). When this is done, monitoring of CO levels in the flue gas is an important step to ensure complete combustion.

Effect of moisture content on fuel value and fuel physical properties and effect of grain dockage as well as the use of off-grade grain should be studied.

Conclusion

A Prairie Fire PEG 060 stove supplied by Prairie Fire Grain Energy co. was used to burn the grain fuels and exhaust test samples were analyzed for greenhouse gas emission through gc analysis. Detailed physical. combustion and economical analysis of grain fuels for heating purposes was performed in this study. Through a number of standardized tests the physical properties of the grains were characterized which pertain to the processing of the grain and may be used for optimization of storage and handling of the grain as well as design parameters of grain heating units. Specifically, Grain particle and bulk densities, the angle/coefficient of internal friction and cohesion, heat of

combustion, chemical oxygen demand, ash content and ash bulk density and emission gas resulting from burning the grain were determined. A number of the grain fuels showed a high amount of gas emission that contributes significantly to greenhouse effect as there was a wide variation of carbon dioxide concentration; oats, canola, triticale, peas and rye produced CO_2 concentrations ranged from 30,400 to 48,500 ppm compared to 50,000 ppm for wood pellets, while wheat, barley and flax produced CO2 concentrations ranging from 55,400 to 62,000 ppm for Methane, flax emitted much larger quantities of the gas than the rest of 674 ppm (way above the average) followed by Canola 142 ppm and for N_2O Canola was the highest with 11 %. This is to compare with ambient air which had concentrations of 404 ppm CO_2, 1.57 ppm Methane and 0.51 % N_2O. Some hydrogen sulfide (H_2S) was detected in the flue gases for the canola, flax grain due to their high oil content while barley showed a less significant amount of the gas. Carbon Monoxide (CO) was not detected in measurable amounts for any of the flue gas samples which ensure complete combustion of the grains but also analysis of the oxygen demand of the combustion process showed that excess air is present which needed to be adjusted for maximum efficiency of the heating unit probably by controlling the combustion fan rpm. Economical analysis revealed that grain energy fuels are likely to be a cost-effective alternative to heating with fossil fuels.

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